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Structure of matter, 9

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Beyond the Standard Models

As noted in SM 8 there are problems with the standard model of particle physics that beg for resolution. Indeed, there are significant unknowns concerning the standard model of cosmology as well—for example, what really is "inflation" and what preceded it? The latter suggests the need for the unification of gravity and quantum mechanics. In addition, both models involve bizarre empirical parameters. Why are the elementary particle masses so wildly different? Why are the strengths of the interactions so different? What is dark matter? What is dark energy and why is its density so small? Why is the energy density in the Higgs field so (relatively) small? According to many theoretical physicists, this hodgepodge of properties is "unnatural" and requires an explanation.

Rudyard Kipling's famous *Just So Stories* (such as "How the Leopard got its Spots," 1902) are fantastically implausible explanations for why things are the way they are. The Higgs mechanism for explaining how the elementary particles got their mass seems a bit like a complicated mathematical Just So Story. On the other hand, a massive (the Higgs interacts with itself, and thereby gets its mass), electrically neutral, spin-zero particle as predicted by the mechanism has been observed, so one shouldn't be completely skeptical. Without similar empirical evidence, other Just So Stories for how to fix the problems of the standard models should be taken with a grain, or two, of salt. Here are a few examples.

- Supersymmetry

Supersymmetry is a newish (theoretical) spacetime symmetry that was discovered in the 1970s. In it, fermions and bosons come in superpartner pairs having the same mass, color, weak isospin, and weak hypercharge. Note that none of the known fermions and bosons are superpartners. In the whimsical supersymmetric nomenclature, the partner of each fermion is a *sfermion* with spin equal to zero. Thus, the partner of the electron is the *selectron*, and of the top quark is the *stop squark*. The partner of each boson is a *bosino* with spin equal to 1/2. The partner of the Higgs boson is the *Higgsino*, and of the *W* boson, the *wino*. As these partners have not been observed, if they exist their masses must be much larger than the known elementary particles. That is, like the weak interaction, supersymmetry must be a spontaneously broken symmetry of nature (broken by some super Higgs field?).

Should supersymmetry exist it accomplishes several nice things. As previously noted, the intrinsic strength of the color interaction is at least ten times greater than that of the electric interaction (at low energies), while the weak strength is about four times greater than the electric. At higher and higher energies the color and weak strengths decrease, while the electric strength increases. Supersymmetry magically allows the color and electroweak strengths to merge at an energy of about 10^{25} eV (about 1000 times less than the Planck energy). This is roughly the estimated energy per particle of the universe at the onset of inflation. That is, prior to inflation, in this scenario, there was a single color-electroweak force–a "grand unification" of the interactions other than gravity. (Perhaps gravity joins these forces into a single force at the Planck scale.) Another nice aspect of supersymmetry is that it might provide the answer to what dark matter is. It might be a sneutrino, a weakly interacting, massive, but electrically neutral, superpartner to the neutrino (a "WIMP"). Finally, the vacuum energy densities of the superpartner fields tend to cancel out. Back in SM2, it was noted that the quantum field theoretic energy operator for photons is of the form

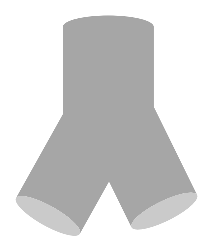
$energy\ operator = \hbar\omega(number\ operator + 1/2)$, and that the vacuum energy density is the infinite sum of all terms of the form $\hbar\omega/2$. This is true for all bosons. But, for fermions $energy\ operator = \hbar\omega(number\ operator - 1/2)$, so the vacuum energy density for fermions is the infinite sum of $-\hbar\omega/2$. If each member of the superpartner pair has the same mass (i.e., the same ω) then the two sums exactly cancel term-by-term. If they have similar, but not equal, masses the cancellation won't be perfect. This would have the potential for answering many of the questions about the unnaturalness of the small magnitudes of dark energy and the Higgs field, for example.

Despite almost universal optimism among particle theorists that superpartners would be discovered at the LHC, there is as yet no such evidence. Proponents of supersymmetry stubbornly argue that the LHC, at present, might have insufficient energy to reveal superpartners. In 2016-18, the LHC will be running close to its maximum design energy; if there is still no hint of superpartners after that, enthusiasm for supersymmetry might well evaporate. Diehards can always invoke the even-higher energy card, but at some point there has to be a way to falsify the supersymmetry hypothesis if it is to be part of conventional science.

- String Theory

Quantum field theory marries special relativity and quantum mechanics and is the theoretical basis for the standard model of particle physics. General relativity marries special relativity and gravity and is the theoretical basis for the standard model of cosmology. As mentioned in SM 8, at high energies and short distances quantum field theory and general relativity are incompatible. *String theory* aspires to reconcile them.

String theory has its origin in the observation, made in the 1960s, that certain spin-mass regularities among the lightest baryons and mesons could be understood if those particles were actually vibrating strings. The success of QCD in explaining and predicting baryon-meson phenomenology renders that primitive idea as unnecessary. But baryons and mesons are composite systems; leptons and quarks are elementary (as far as we know). Extending the notion of intrinsic vibrations to the elementary particles has given rise to "string theory," now a forty year-old theoretical enterprise, which, though promising, is still not well understood or established.



In this picture of reality, elementary particles consist of a kind of elementary elastic stuff, the various vibrational modes of which give rise to all of the particle properties. In string theory, particles are not points. The figure to the right (where time increases upward) is a cartoon showing two string "particles," in this case tiny loops of string stuff, interacting and forming a third particle (like a pair annihilation vertex, for example). In the interaction the loops open up and reconnect as one loop. There are no interactions at a point, as in quantum field theory. Of course, viewed at a much larger scale, the interaction seems point-like, but at the Planck length scale (the spatial extent of the string-string interaction) it is not. So string theory makes it possible to unite gravity with quantum field theory.

In the 1920s, a curious extension of general relativity, due to Theodor Kaluza and Oskar Klein, demonstrated that gravity and classical electrodynamics could be unified if spacetime had *four* spatial dimensions and one time dimension. In the Kaluza-Klein theory, every point in ordinary 3+1-spacetime has a small (1-D) circle attached to it. Einstein's equations for gravity in 4+1 dimensions leads to: gravity in 3+1 dimensions; plus vector fields that obey Maxwell's wave equation–something that looks like electromagnetism in 3+1 dimensions; plus a scalar field that just winds around the attached extra dimension. Supposedly *we* don't "travel" in the fourth spatial dimension because we are so big and the little attached circles are so small–technically they are "compact" and small. The mass spectrum of particles associated with the extra scalar field is inversely proportional to the radius of the attached circle; if that radius is really small then the mass spectrum is really big. Usually, the mass of the extra scalar field is taken to be zero and its possible existence is ignored.

String theory shares the Kaluza-Klein hypotheses of extra dimensions and compactification. One of the most discussed (of the several possible) string theories is *superstring theory*, which includes fermionic and bosonic supersymmetric partners. One of the string particles of superstring theory has the attributes (zero electric charge, zero mass, spin = 2) of a graviton, a quantum of gravity. Thus, quantum gravity is a natural consequence of the theory. This theory has nine spatial dimensions and one time dimension. In order to explain why observed spacetime is 3+1 dimensional, six of the spatial dimensions of superstring theory are supposedly compactified and small. It has been conjectured that prior to inflation the universe might have had 9 equally small spatial dimensions, but during inflation three expanded rapidly to very large size; who knows? There are many ways of doing compactification and many fundamental vibrational modes that strings (and membrane-like sheets) can execute in six dimensions (some estimates are like 10^{500}, eeek!). As each of these represents a different set of elementary particles with different interactions, all *a priori* equally valid, string theory seems to suggest an enormous number of theoretically possible physical universes. In this sense any crazy set of physical parameters is as "natural" as any other. Unfortunately, string theory provides no hint as to why we happen to occupy the universe we are in. (The "anthropic principle," that because we are *here* the universe must be the way it is, isn't very compelling–and not testable, i.e., not real science.) As of now, there is no evidence in LHC data for either supersymmetry or extra dimensions. Of course, adherents to string theory note that the LHC might not have enough energy to see such things. Such dodges raise the question of whether string "theory" is really a theory in the usual scientific meaning. Maybe it is the most elaborate Just So Story humans have ever invented.

- Loop Quantum Gravity

In superstring theory, string stuff occupies a predefined 9+1 dimensional spacetime arena. General relativists who are strict constructivists don't like that: they say that the structure of spacetime should not be predefined, but rather constructed by the matter it contains. Furthermore, in general relativity spacetime is the gravitational field, so instead of fields filling spacetime, as in the Standard model of Particle Physics, fields couple to and create the field that they reside in. A primary competitor to superstring theory, *loop quantum gravity*, is based on this premise.

General relativity is singular below the Planck length. Black holes are singular at $r = 0$; the FLWR cosmology is singular at $a = 0$. According to general relativity mass and energy densities blow up under these conditions. General relativity makes nonsensical predictions at small distances and high energies. Loop quantum gravity (LQG) prevents such singularities by postulating that *there is no spacetime below the Planck length*. At the Planck scale in LQG spacetime *effectively* consists of "loops of space and time." Macroscopic spacetime, in LQG, consists of a seething "foam" of intersecting loops.

Curiously, in LQG area and volume have corresponding quantum operators, analogous to the energy and momentum operators of quantum field theory. Like the latter, the LQG operators operate on a "spacetime wavefunction," resulting in measurable area and volume values. As is the case for the energy levels of atomic electrons, values of the areas of spacetime surfaces and volumes of spacetime regions are quantized in LQG. (These level differences are small and, as a consequence, on length scales large compared to the Planck scale area and volume appear to take on essentially continuous values, as would be expected.) One consequence of this quantization is that LQG predicts that the surface area of a black hole is composed of discrete units of area. By counting these units it is possible to assign an "entropy" (a measure of the available states of a macroscopic thermal system) to the black hole's surface (horizon) area. The result is in exact agreement with a forty year-old speculation that black holes have effective entropies proportional to their areas and temperatures inversely proportional to their masses, and emit thermal ("Hawking") radiation.

The Holy Grail of string theory is to account for every known (and unknown) particle property by invoking supersymmetry and extra dimensions. LQG has a similar goal, but without the extra particles and dimensions. In the 1950's, John Wheeler (Feynman's PhD mentor) proposed that elementary particles might be made of "geons," tiny gravitational excitations. LQG provides a potential theoretical framework for realizing Wheeler's vision. Thus, instead of string stuff, elementary particles might be made of quanta of spacetime.

When LQG is endowed with a *positive* cosmological constant, the seething foam of loops averages out, at large length scales, to a description of spacetime that is identical to general relativity and quantum mechanics. Interestingly, the marriage of gravity and quantum mechanics achieved *in superstring theory* appears to require a *negative* cosmological constant. But, of course, if dark energy is interpreted as a cosmological constant, its value is positive. This encourages LQG opponents of string theory to claim that this single observation already falsifies all of string theory.

Along these adversarial lines, Lee Smolin, one of the pioneers of LQG, tells the following joke: A string theorist hearing a talk about loop quantum gravity says, "That's a very beautiful theory, but it has three big faults: Space only has three dimensions, the cosmological constant is positive, and there is no supersymmetry!" To which the speaker replies, "You mean, just like the real world?"

In any case, whatever particle/gravity theory will look like a hundred years from now, it will have to somehow accommodate all of the well-established phenomena we have discussed in this course.